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ORIGINAL RESEARCH

FOAM ROLLING AND INDICES OF AUTONOMIC RECOVERY FOLLOWING EXERCISE-INDUCED MUSCLE DAMAGE

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ABSTRACT

Background: With the increased popularity of foam rolling as a recovery tool, it is important to explore possible mechanisms of action toward mitigating soreness and restoring athletic performance.

Purpose: The purpose of the present experiment was to assess the influence of foam rolling on gross measures of physical performance and indices of autonomic function following exercise-induced muscle damage (EIMD).

Method: In a between-group design, 40 participants performed a session of 40x15 meter sprints, inducing muscle damage. Immediately following sprinting and in the four days following, heart rate variability and pulse wave velocity were recorded, in addition to perceived muscle soreness, vertical jump, and agility. Nineteen subjects (mean ± sd; age 23.1 ± 5.0 yrs; BMI 25.6 ± 3.3 kg.m-2) foam rolled their quadricep, gluteal, and gastrocnemius areas prior to testing each day, while 21 (mean ± sd; age 24.2 ± 3.4 yrs; BMI 26.3 ± 4.0 kg.m-2) served as a control. Mean values from three days of baseline testing were compared to the area under the curve during five days of recovery after the performance of the repeated sprint protocol. The area under the curve was calculated by summing all five values recorded the recovery days, then these data were compared by condition using a two-tailed Mann-Whitney U test (alpha level = 0.05).

Results: Following EIMD, neither heart rate variability, pulse wave velocity, agility, nor vertical jumping performance versus previously measured baseline differed significantly between groups ($p > 0.05$). Perceived muscle soreness was significantly diminished in the foam rolling condition ($p < 0.05$). Mean Day 1 to Day 5 values for perceived muscle soreness in controls were 16.52, 30.24, 24.48, 17.19, and 11.10. Mean Day 1 to Day 5 values in foam rolling subjects were 12.63, 24.63, 21.79, 15.05, and 10.16.

Conclusion: Foam rolling may be useful for reducing soreness following damaging exercise, but according to the outcomes measured in the present experiment, the effect does not appear to be mediated by the autonomic nervous system.

Level of evidence: 2c

Key words: Foam rolling, heart rate variability, induced muscular soreness, movement system, pulse wave velocity, sprinting

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INTRODUCTION

Exercise-induced muscle damage (EIMD) often follows intensive exercise consisting of large volumes of eccentric muscle actions, typically occurring with decelerating activities.[1] Exercising in this manner can result in intracellular muscle damage, potentially accompanied by impaired muscle function and delayed onset muscle soreness (DOMS).[2] Additionally, EIMD may result in swelling and inflammation, along with increased proteins in the blood.[3] While the precise mechanisms underlying EIMD are unclear, mechanical and metabolic pathways are thought to contribute.[4,5] For example, a proposed mechanical pathway described by Proske and Morgan involves sarcomere disruption due to a high degree of myofibril tension.[4] Comparatively, a proposed metabolic pathway described by Tee et al. involves a delayed inflammatory response, oxidative stress, and excitation-contraction coupling impairment via disruption of calcium homeostasis.[5] A certain degree of EIMD is a normal and potentially useful stimulus for physiological adaptations associated with exercise.[6] However, excess damage and the associated performance decrements can hinder athletic performance, and potentially disrupt a training cycle.[6] Thus, interventions alleviating EIMD symptoms may benefit athletes. Foam rolling (FR), a commonly used therapeutic practice,[7] may serve this purpose.

Foam rolling is a self-massage technique performed on a foam cylinder[8]. Cheatham et al.[9] reported that 81% of 1042 physical therapists, athletic trainers, and fitness professionals surveyed use FR in their practice. Further, sixty-one percent of these respondents reported using FR as a pre- and post-exercise intervention. Although FR does not appear to enhance acute strength and power performance,[10,11,12] it has been shown to acutely increase joint range of motion (ROM),[7,11,12,13,14,15,16,17,18] while preserving strength and power after exercise-induced muscle damage.[7,16,17,18] Thus, researchers have suggested that FR prior to physical activity is an optimal way to increase ROM, while avoiding performance decrements observed with static stretching.[7,17]

Expedited recovery from exercise may be another benefit of FR. Researchers have suggested that FR can reduce the sensation of DOMS, and may enhance athletic performance in the days following demanding exercise.[8,19,20,21] For example, D'Amico and Gillis[19] assessed the influence of FR on agility, muscular power, perceptions of muscle soreness, and flexibility in the days following a bout of high-volume sprinting (40 x 15 m sprints). The authors reported that FR improved recovery of agility compared to a control (CON). Similarly, Jay et al.[20] investigated the influence of roller massage on muscle soreness, pain pressure threshold (PPT), and ROM following the induction of DOMS (10 sets of 10 stiff-legged deadlifts). The authors reported significant reductions in muscle soreness, and increases in PPT compared to CON. Macdonald et al.[8] assessed the efficacy of FR as a recovery tool on various measures, including muscle soreness, flexibility, vertical jump (VJ), and muscle activation before and 24 hr, 48 hr and 72 hr after EIMD (10 sets of 10 back squat repetitions at 60 % 1 RM). The authors reported reductions in muscle soreness, and improvements in VJ and muscle activation. Pearcey et al.[21] assessed the efficacy of FR as a recovery tool using 30 m sprint time, standing broad jump length and the agility T-test. These measures were obtained before and 24 hr, 48 hr and 72 hr after EIMD (10 sets of 10 back squat repetitions at 60 % 1 RM). Pearcey et al.[21] reported that FR following EIMD improved sprint time, standing broad jump, and the agility T-test compared to CON. Taken together, the aforementioned studies suggest that FR may enhance indices of recovery following intense, high-volume sprinting or resistance training.

While the available evidence supports the use of FR as an exercise recovery tool,[8,19,20,21] the underlying mechanisms are unclear. Several have been proposed, but evidence linking any physiological occurrence to the presence and extent of recovery following demanding exercise is not currently available. In a review, Behm and Wilke have suggested that the commonly-used term *self-myofascial release* is inappropriate. According to those authors, the manual forces applied during FR are insufficient to immediately deform connective tissue, and any changes in stiffness appear to occur on a delayed basis, indicating either proprioceptive tie-ins, or hydration alterations. Additionally, nonlocal changes in pain typically observed following FR suggest an activation of global pain modulatory responses, and increased parasympathetic nervous system relaxation.[22] For example, Aboodarda et al. reported similar increases in contralateral limb pressure pain threshold to their ipsilateral counterparts following roller massage.[23] Cavanaugh et al. reported similar resistance to pain associated with tetanic twitch following roller massage, both ipsi- and contralaterally.[24] While the specific physiological underpinnings of these observations are unclear, Jay et al. have suggested that the activation of descending inhibitory pathways via the central gray matter-opioid system and oxytocin may explain reductions in pain following FR.[20] Alternatively, Macdonald et al.[8] have suggested that FR likely acts by reducing neural inhibition due to accelerated connective tissue recovery, potentially resulting in decreased inflammation and increased mitochondrial biogenesis. These authors have suggested that this may decrease nociceptor activation and increase communication from afferent receptors in the connective tissue. In this view, the resulting improved communication may permit better sequencing and recruitment patterns, enhancing performance markers compared to a group recovering from muscle damage who did not use FR.

While the previously discussed mechanisms are plausible, a cause and effect relationship between any neural influence of FR and enhanced recovery in the days following damaging exercise has yet to be identified. Though the previously discussed crossover effect would seem to confirm at least some neural influence of FR,[14] any role this may have in enhanced recovery is speculative at present. Heart rate variability (HRV)[25] and pulse wave velocity (PWV),[26] both markers of autonomic nervous system tone, may shed light on the issue. Heavy training loads can result in cumulative stress, and the magnitude of such a response can be observed by variations in autonomic balance, and indirectly assessed with HRV.[25] Lastova et al.[27] investigated the influence of FR on acute measures of HRV. Vagal tone, sympathetic activity, and sympathovagal balance were all improved following FR, indicating enhanced relaxation and suggestive of enhanced recovery, with the final measure taken 30 min post FR.[23] While HRV is a reflection of the autonomic status of the heart, PWV can provide insight into autonomic balance via the stiffness of the arterial system, which increases in conjunction with sympathetic output.[26] Okamoto et al.[26] investigated the influence of FR on PWV. Pulse wave velocity was improved following FR, indicating a decrease in arterial stiffness, which is associated with decreased sympathetic output.[26] The final measure recorded by Okamoto et al.[26] was also conducted 30 min post FR. These findings suggest that FR may temporarily decrease sympathetic and increase parasympathetic nervous system activity. However, given the 30 min measurement windows, it is unclear whether these benefits may extend to the hours and days following treatment. Further, it is unclear whether these benefits extend to individuals experiencing EIMD, or have any relationship with enhanced recovery of performance markers. Therefore, the purpose of the present experiment was to assess the influence of foam rolling on gross measures of physical performance and indices of autonomic function following exercise-induced muscle damage. It was hypothesized that following EIMD, FR would result in less impairment of agility and VJ performance, a decrease in perceptions of muscle soreness, an increase in HRV, and a decrease PWV, compared to CON.

METHODS

Subjects

Nineteen healthy adults aged 19 to 38 years (mean $\pm$ sd; age 23.1 $\pm$ 5.0 yrs; BMI 25.6 $\pm$ 3.3 $kg \cdot m^{-2}$; 13 male, 6 female) completed the experimental FR protocol, while 21 adults aged 19 to 30 (mean $\pm$ sd; age 21.9 $\pm$ 2.7 yrs; BMI 24.2 $\pm$ 3.4 $kg \cdot m^{-2}$; 12 male, 9 female) served as a non-FR control (CON). Subjects were verbally informed of all procedures, informed of the potential risks and benefits of the study, and if willing to participate, read and signed an informed consent form prior to participation. All procedures were approved by the University Institutional Review Board (IRB application number: 011916-1). Based upon previous research, approximately eight to 20 subjects per condition in a between-subject experimental design were determined as sufficient to observe a significant difference in the primary outcome measure of muscle soreness.[8,19,20,21] Potential subjects were excluded if they 1) had a pre-existing lower extremity injury or muscular soreness, or 2) had foam rolled in the last 30 days. Subjects were excluded if they had already participated in similar research where muscle damage was induced by a repeated sprint protocol. Each subject was instructed to refrain from strenuous physical activity and alcohol consumption for twenty-four hours prior to testing.

Experimental Design

A counterbalanced, independent-group design was used to assess how FR influences recovery following EIMD. Five post-EIMD testing days were preceded by three days of baseline tests and familiarization sessions. A repeated sprint protocol consisting of 40, 15 m sprints with a five m deceleration zone was used to induce muscle damage. Dependent variables included perception of muscular soreness, HRV, PWV, VJ, and agility T-test time. Performance-based dependent variables were chosen to assess attributes athletes would hope to restore as quickly as possible after muscle damage induced by training, practice, or competition, along with indices of autonomic recovery. Within the context of this study, the independent variable was FR following EIMD, or not FR. The dependent variables were used to assess differences in recovery between subjects who foam rolled daily versus those not utilizing any type of recovery modality. A repeated sprint protocol was chosen as the means by which to induce muscle damage because of its demonstrated reliability,[28] and the extent to which the findings might pertain to a wide array of sporting scenarios.

Procedures

This experiment took place over two weeks. During week one, subjects attended the lab three days, once per day, from Wednesday to Friday. During the first session of week one, subjects were assigned to either FR or CON in a counter-balanced order. After group assignment, and prior to a standardized pre-testing battery warm-up (described below), subjects in CON completed the testing battery consisting of perceptions of muscle soreness, HRV, and PWV. These were performed prior to the warm-up to remove any influence of acute exercise on those variables. Then, after the warm-up, the non-fatiguing performance testing battery comprised of VJ and the agility T-test was completed. Subjects in FR followed the same order of testing, but completed the FR protocol (described below) following the general warm-up, perceptual and autonomic assessments, and prior to the performance testing battery. Subjects in CON were provided with identical instructions to FR, but without an overview of the FR treatment. This protocol was followed during each of the subjects' three familiarization visits to the lab during week one. Testing took place at the same time of day throughout the study to minimize the influence of diurnal variation on performance. Testing was conducted in the same physical spaces in front of the same individuals throughout data collection to control for audience effects. In addition to providing comparison data, baseline testing was conducted over the three days to minimize the influence of learning effects during testing. During week two, subjects attended the lab on five days, once per day. On the evening of Day 1, subjects underwent a repeated sprinting protocol (described below). Ten minutes thereafter, subjects in the experimental group underwent the 25- minute FR intervention while CON stood and rested for an equivalent amount of time. Both groups performed the testing batteries immediately thereafter. On the evenings of Day 2 through Day 5, both CON and FR completed the perceptual and autonomic measures prior to any exertion, then performed the standardized pre-testing battery warm-up (50 jumping jacks, 30 high knees [15 per leg], 10 push-ups, and 10 squats). Subjects in FR then performed the FR protocol (described below), then immediately performed the remainder of the testing battery. Subjects in CON immediately performed the remainder of the testing battery after the warm-up.

Description of the Foam Rolling Intervention

Using a protocol adapted from D'Amico and Gillis,[19] subjects performed six foam rolling movements targeting four portions of the thigh, the gluteus maximus, and gastrocnemius muscles using a high-density foam roller (TheraBand, Performance Health, Warrenville, IL, USA) on both the right and left legs for two 60 second (s) bouts each (Figure 1).[19] Each roll was timed to a cadence with a metronome allowing for five seconds per roll within the 60 s period. In performing exercises for the thigh, subjects were instructed to place their body mass on the foam roller,

Figure 1. *Foam rolling intervention technique. Top left: anterior thigh. Top right: medial thigh. Middle left: lateral thigh. Middle right: posterior thigh. Bottom left: Gastrocnemius. Bottom right: Gluteus Maximus.*

starting at the proximal aspect of the thigh and then rolling gradually towards the knee. Once the foam roller reached the distal aspect of the thigh, subjects returned the foam roller to the proximal aspect in one fluid motion. This sequence continued for the remainder of the 60 s trial. The FR protocol covered the anterior, lateral, posterior, and medial aspect of the thigh. For the gluteal muscles, each subject was instructed to sit on top of the foam roller, placing both hands on the floor behind them. The subject crossed their right/left leg over their left/right knee, positioning their body so the left/right gluteal muscle was in contact with the foam roller. Subjects were instructed to undulate back and forth, with the foam roller running in line with the origin (the gluteal surface of ilium, lumbar fascia, sacrum, and sacrotuberous ligament) and insertion (gluteal tuberosity of the femur and iliotibial tract) of the gluteus maximus muscle. For the gastrocnemius muscles, the subjects were instructed to place their body mass on the proximal aspect of the gastrocnemius muscle and then gradually work down the calf using smooth, fluid movements, moving the foam roller from the proximal to the distal aspect of the muscle.

Description of Muscle Damage Protocol

Prior to the muscle damage protocol on the evening of Day 1, subjects performed a general warm-up consisting of five laps around the perimeter of a basketball court followed by a sprinting-specific dynamic warm-up consisting of soldier walks, butt kicks, high knees, walking on toes, cariocas, and side steps over with a squat. Subjects then completed four 15 meter sprints progressing from 25 % of maximal intensity (sprint 1), to 50 % (sprint 2), to 75 % (sprint 3), to 100 % (sprint 4). This sprinting-specific warm-up performed prior to the muscle damage protocol differed from the aforementioned warm-up used on other testing days. The sprinting-specific warm-up was intended to reduce the likelihood of a running injury, while the pre-testing battery warm-up was intended to promote more generalized preparedness and increases in tissue temperature. Repeated sprinting was used to induce muscle damage in subjects. Specifically, subjects completed 40, 15 m sprints with a 5 m deceleration zone. This protocol has successfully induced muscle soreness in similar research.[19]

Perception of Muscle Soreness

A PainTest™ FPN 100 Algometer (Wagner Instruments, Greenwich, CT, USA) was used to measure muscle soreness of the quadriceps, hamstrings, gluteus maximus and gastrocnemius muscles after EIMD. The algometer was used to apply 30 N of force to each muscle belly. For the quadriceps, pressure was applied to the rectus femoris at the mid-way point between the inguinal crease and the distal border of the patella. For the hamstrings, pressure was applied at the mid-way point between the ischial tuberosity and the popliteal fossa, in the center of the posterior thigh. For the gastrocnemius, pressure was applied at the mid-way point between the popliteal fossa and the most inferior surface of the muscle belly, between the lateral and medial heads of the muscle. The subject gave a verbal rating of pain from zero (no pain) to 10 (most painful) using a categorical pain scale.[29] The main drawback of using a category scale is it only allows inferences to be made about the rank-order of the different sensations. To overcome these issues Green et al.[30] developed a scale of sensation magnitude with apparent ratio properties and called it the general labeled magnitude scale (gLMS).[30] The gLMS scale is bounded at the bottom by 'no sensation' and at the top by 'strongest imaginable sensation'. The key feature of the gLMS is that its verbal descriptors (barely noticeable, weak, moderate, strong, and very strong) are placed quasi-logarithmically at locations along a straight line that are determined by estimations of their perceptual magnitudes. The gLMS is capable of generating ratio-level data in many sensory modalities,[30] has been employed in similar research,[19] and was used in this study as an additional measure of muscle soreness. Subjects in both groups reported gLMS following five 18-inch body weight step-ups on each leg. The ICC for the gLMS was .53.

Lower Body Power

A VJ test was used to assess lower body power. Vertical jump testing was based on the protocol outlined in The Canadian Physical Activity, Fitness and Lifestyle Approach (CPAFLA) manual.[31] A commercial Vertec (Vertec, North Easton, MA, USA) device was used. Without a stutter or preparatory step, subjects were instructed to flex their knees and hips into a partial squat, coming to a full stop at the bottom of the motion to eliminate the stretch reflex. Subjects then jumped up with the dominant arm reaching upward, pushing the highest possible vane. The average of three trials was recorded to the nearest 0.5 inches. The ICC for VJ was .97.

Agility

The T-test was used to assess subject agility. Four cones were arranged in the shape of a T. Beginning at the bottom of the T, subjects were instructed to sprint 10 yards forward, shuffle five yards to the left without any crossing over of the feet or turning of the body, shuffle 10 yards to the right in the same fashion, shuffle five yards to the left, and then backpedal 10 yards to the original starting point, touching each cone that formed the T along the way. The average of two trials was recorded to the nearest 0.1 second. Disqualification of a trial occurred if the subject failed to touch the base of any cone, crossed one foot in front of the other or did not face forward while shuffling.[32] The ICC for the T-test was .37.

Heart Rate Variability

An ithlete™ heart rate variability smart phone application (HRV Fit Ltd, Southampton, UK) was used to assess ultra-short-term root mean square of successive R-R intervals (RMSSD). Descending RMSSD during intensive training has been associated with increased fatigue.[33,34] Subjects rested quietly for at least 10 minutes upon entry to the lab. A Polar Heart Rate Sensor H1 (Polar Electro Oy, Kempele, Finland) was affixed to the subject, and an iPhone 5 (Apple, Cupertino, CA) with the application installed was provided. While sitting quietly, subjects followed instructions from the software to inhale through the nose and exhale through the mouth on a set cadence for 55 seconds. Once complete, a RMSSD value was provided by the application. The ICC for HRV was .17.

Pulse Wave Velocity

The iWorx IX-TA 220 and Labscribe software (iWorx, Dover, New Hampshire, USA) was used to assess brachial-finger pulse wave velocity, indicative of arterial stiffness. Subjects rested quietly for at least 10 minutes upon entry to the lab, then laid on a table for measurement. An electrode was placed on the anterior surface of each wrist, and on the lower right abdomen. A plethysmograph was affixed to a palpable brachial pulse location with surgical tape on the left arm. A recording was initiated, and allowed to run for at least two minutes. Once two minutes had elapsed, the researcher identified five consecutive, suitable EKG and brachial pulse waveforms. Using the Labscribe software, the researcher measured the duration between each R wave, and the subsequent pulse wave peak (R-Pulse Wave). The five duration values were then averaged, with the value expressed in milliseconds. The plethysmograph was then affixed to the volar surface of the middle finger with a hook and loop fastener. The process described for the brachial pulse was repeated for the middle finger. Distance between the brachial and finger measurement sites was assessed by tape measure in mm. This value was divided by the difference between the mean brachial and finger R-Pulse wave intervals. The resulting pulse wave velocity value was expressed in m/s. The ICC for PWV was .23.

Statistical Analyses

Mean values from week one familiarization testing were used to calculate baseline data. All week two data were then compared to how they changed from baseline (△). The area under the curve (AUC) was then calculated for each subject, by condition, by summing the week two scores collected from Day 1 to Day 5. All data were then assessed for normality of distribution using the Kolmogorov Smirnov test. Normally distributed data were compared by condition using a two-tailed independent t-test. If data were not normally distributed, the non-parametric two-tailed Mann-Whitney U test compared conditions. The alpha level was set at 0.05. All data analysis was completed using GraphPad Prism 5.0 (GraphPad Software San Diego, CA, USA).

The magnitude of effect was also calculated for significant treatment effects. Specifically, mean differences were first calculated between condition means as they changed (Δ) from baseline (i.e. FR [minus] CON). Ninety-percent confidence intervals were calculated to surround mean differences (expressed as mean difference, $\pm CI_{90\%}$), according to the approach of Hopkins et al.[35] Confidence intervals were calculated using the formula:

$$\bar{X} \pm 1.65 \times \text{ Standard error of the mean},$$

whereby the standard error of the mean was calculated using the formula:

$$\frac{Sample\ \ standard\ deviation}{\sqrt{CON\ sample}}.$$

Thresholds for a small, moderate, and large effects were calculated as 0.3, 0.9, and 1.6 of the standard error of the measurement, respectively.[35] The standard error of the measurement was calculated using the formula:

$$SDtest \cdot (\sqrt{1 - Rtest}),$$

whereby *Rtest* equated to the mean intra-class correlation coefficient (ICC) obtained from familiarization 2 vs. familiarization 3. This approach may be considered conservative, as a learning effect would be expected to increase variability across the familiarization sessions. Finally, *SDtest* equated to the standard deviation of the familiarization test scores.

Results

Subject Characteristics

The mean (SD) subject baseline scores for all tests are displayed in Table 1. No significant differences in participant characteristics or mean values from the three-day baseline testing battery were observed between conditions ($p > 0.05$).

Perceptions of Muscle Soreness

Figure 2 displays the mean (SD) perception of muscle soreness by condition. Perception of muscle soreness as measured by the gLMS significantly differed by condition ($p < 0.05$). Specifically, a two-tailed Mann Whitney U test showed a significant

Table 1. *Mean (SD) subject characteristics at baseline in foam rolling (FR) and control (CON) conditions.*

Variable	CON (n=21)	FR (n=19)
Weight (kg)	69.91 (14.71)	73.92 (7.97)
Age (yrs)	21.86 (2.67)	23.11 (5.07)
Height (m)	1.69 (0.10)	1.72 (0.08)
BMI ($kg \cdot m^{-2}$)	24.24 (2.39)	25.55 (3.33)
Muscle soreness (gLMS)	3.81 (6.89)	5.26(6.81)
Muscle pain: Quadriceps (VAS)	0.55 (0.96)	1.11 (1.74)
Muscle pain: Hamstrings (VAS)	0.69 (0.98)	1.16 (1.94)
Muscle pain: Calf (VAS)	0.60 (1.22)	1.32 (1.99)
Heart Rate Variability (RMSSD)	78.38 (6.66)	82.53 (6.91)
Pulse Wave Velocity (M/S)	8.41 (1.54)	8.88 (3.82)
Vertical Jump height (inches)	16.84 (5.40)	19.74 (4.80)
Agility (s)	11.92 (3.07)	11.79 (1.60)

gLMS = General labelled magnitude scale, VAS = Visual analog scale, RMSSD = root mean squared of successive R-R intervals, M/S = meters per second, s = second.

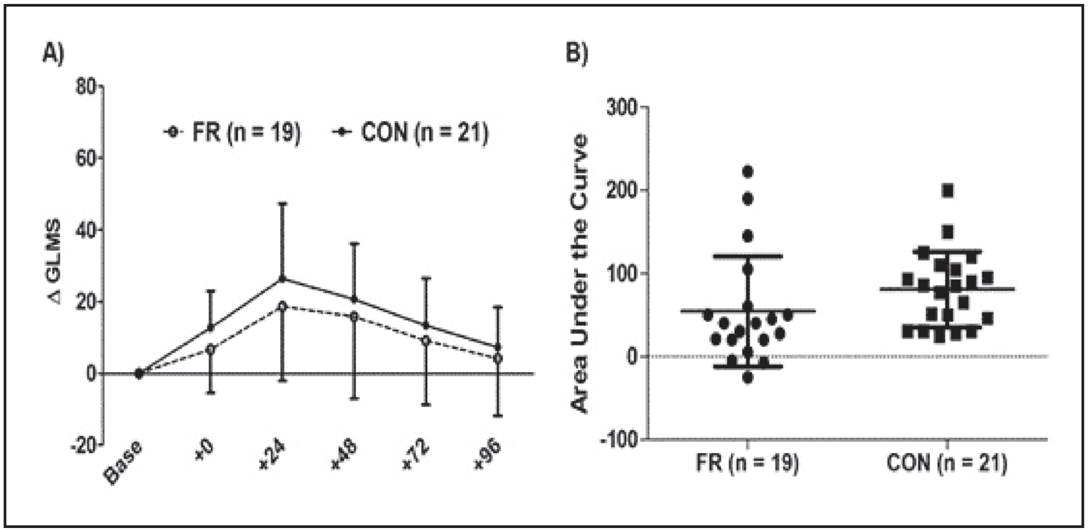

Figure 2. *Perceptions of muscle soreness in foam rolling (FR) and control (CON) conditions, as measured by general labelled magnitude scale (gLMS). A) Mean change in perceptions of muscle soreness B) Area under the change (Δ) in gLMS curve. A two-tailed Mann Whitney U test showed a significant difference by condition (p = 0.0127) in the area under the Δ Time (s) agility curve, with FR resulting in lower perceptions of muscle soreness compared to CON.*

difference by condition (p = 0.0127) in the Area Under the Δ gLMS Curve (AUC), with FR resulting in diminished perceptions of muscle soreness compared to CON. The AUC was higher in CON (80.48 ± 45.56) than FR (54.39 ± 66.20), indicating larger increases in soreness from baseline throughout the testing week in CON. Mean Day 1 to Day 5 values for gLMS in CON were 16.52, 30.24, 24.48, 17.19, and 11.10, respectively, equating to a verbal descriptor approaching 'Strong' perceptions of muscle soreness. Mean Day 1 to Day 5 values in FR were 12.63, 24.63, 21.79, 15.05, and 10.16, respectively, equating to a verbal descriptor closer to 'Moderate' compared to 'Strong' perceptions of muscle soreness reported by the CON group.

The magnitude of effect was also calculated by finding the mean difference in the Δ perception of muscle soreness between CON and FR, and then building a 90 % confidence interval ($\pm CI_{90\%}$) around the mean difference for each testing day. These data are displayed in Figure 3. Rather than representing a range of individual responses from the study, this magnitude-based approach suggests with 90 % certainty that the true change in perception of muscle soreness after EIMD measured between any two conditions will fall in the 'small', 'medium' or 'large' effect ranges shown in Figure 3. Further, if there is no real difference between two conditions, the mean difference, $\pm CI_{90\%}$ will overlap zero, shown as a solid line in the center of the figure. With this, the reader will observe small to medium effects of FR in reducing perception of muscle soreness immediately post-sprinting. From 24 to 96 hours post sprinting, the confidence interval boarders 'no effect' at its lower bound to 'medium effects' (+48 hrs, +72 hrs, +96 hrs) and approaching 'large effects' (+24 hrs) at its upper bound.

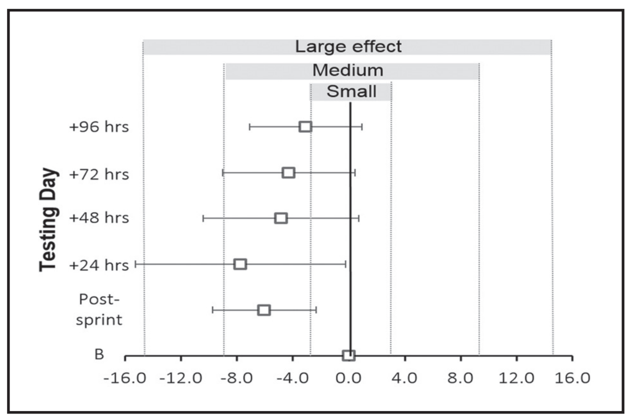

Figure 3. *Mean difference, $\pm CI_{90\%}$ for the perception of muscle soreness in general labelled magnitude scale (gLMS) units compared by condition across the testing week. These data suggest with 90% certainty that the true change in perception of muscle soreness after exercise-induced muscle damage measured between conditions will fall in the "small," "medium," or "large" effect ranges. If there is no real difference between conditions, the mean difference, $\pm CI_{90\%}$ will overlap zero. The data show favor for foam rolling (left of zero), indicating a benefit toward reducing perceptions of muscle soreness.*

No significant differences were observed between conditions in the perception of muscle pain measured in response to 30 N of pressure applied by an algometer applied to the quadriceps, hamstrings and calf ($p > 0.05$). The mean (SD) pain response did not exceed 2.53 $\pm$ 2.48 across all conditions and muscle bellies, which equates to a location less than halfway between 'no pain' at point zero, and 'moderate pain' at point five on the zero to VAS 10 scale.

Lower Body Power

No significant differences were observed between conditions in the vertical jump ($p > 0.05$). The absolute mean (SD) VJ times across both conditions from Baseline, across the testing week were: 19.04 (4.6) in, 17.96 (4.3) in, 17.70 (4.5) in, 17.71 (4.3) in, 18.20 (4.3) in, and 18.28 (4.4) in, respectively.

Agility

No significant differences were observed between conditions in agility ($p > 0.05$). The absolute mean (SD) agility times across both conditions from Baseline, across the testing week were: 11.71 (1.42) s, 12.52 (1.90) s, 12.52 (1.63) s, 12.07 (1.86) s, 12.20 (1.71) s, and 12.29 (1.72) s, respectively.

Pulse Wave Velocity

No significant differences were observed between conditions in pulse wave velocity ($p > 0.05$). The absolute mean (SD) PWV values across both conditions from Baseline, across the testing week were: 8.63 (2.83) m/s, 8.47 (2.44) m/s, 9.13 (2.62) m/s, 8.79 (2.80) m/s, 9.29 (4.35) m/s, and 8.80 (3.90) m/s, respectively.

Heart Rate Variability

No significant differences were observed between conditions in heart rate variability ($p > 0.05$). The absolute mean (SD) HRV values across both conditions from Baseline, across the testing week were: 80.4 (7.0), 75.2 (9.2), 81.1 (5.7), 79.8 (7.8), 77.9 (9.4), and 78.9 (8.5), respectively.

Discussion

The present study sought to discern whether FR influences indices of autonomic recovery alongside gross performance measures following sprinting induced muscle damage (EIMD). The first important finding is that the sprint protocol was effective in inducing muscle soreness across both conditions. Specifically, subjects in both FR and CON experienced 'moderate' to 'strong' perceptions of muscle soreness (Figure 3). The second important finding is that FR appeared to reduce perceptions of muscle soreness compared to the control condition. These findings are in general agreement with Jay et al.,[20] Macdonald et al.,[8] and Pearcey et al.,[21] whom all observed that FR following EIMD or DOMS reduced soreness. Though some previous work investigating perceptions of muscle soreness following EIMD induced by sprinting have not observed a benefit from FR,[19] subjects in that study rated soreness while standing still. This should be contrasted to the present experiment, in which subjects rated soreness while stepping up and down from an 18-inch elevation. Reduced perceptions of muscle soreness during movement *per se* may explain improvements in gross motor performance typically observed throughout the literature. In any case, the results of the present experiment suggest that there may be possibly beneficial effects of FR on reducing the perception of muscle soreness immediately after sprinting, but the effects seem to become more variable across the five testing days, whereby some participants seem to experience no or trivial effects, and others may experience moderate to large effects (Figure 3). Because there are no clear harmful effects i.e. that participants feel more muscle soreness with FR, it seems there may be little risk associated with FR up to 96 hours post muscle damage protocol.

The physiological underpinnings of this reduced soreness following FR remain unclear. Varying explanations involving activation of descending inhibitory neural pathways,[20] or decreased nociceptor activation,[8] have been suggested. Cavanaugh et al. reported pain reduction in the limb contralateral to the one rolled. The authors suggested that these findings support previous work indicating that noxious stimuli can impart a generalized inhibition of pain perception.[23] Similarly, Aboordada et al. speculated that roller massage provided analgesic effects via the ascending pain inhibitory system, the descending anti-nociceptive system, and parasympathetic stimulation.[24] While some or all of these may have contributed to the findings in the present investigation, it is also possible that participants in the FR condition experienced a placebo effect, causing them to subconsciously adjust ratings of muscle soreness. Future researchers should investigate the mechanisms resulting in reduced perceptions of muscle soreness following FR.

Foam rolling did not appear to alter recovery of squat jumping height following exercise-induced muscle damage under the conditions of the present experiment. This finding stands in contrast to previous investigations, which have found that VJ recovery was enhanced by FR 48 hr post EIMD.[8] and broad jump recovery enhanced by FR 72 hr post EIMD.[21] Both of the aforementioned studies however utilized a countermovement jump, which does not feature a pause at the bottom of the movement. In an investigation where a squat jump was utilized instead of a countermovement jump i.e. a pause was present at the bottom of the movement, FR did not expedite recovery of vertical jumping height,[19] a finding that is in agreement with the present experiment. From these findings it might be inferred that FR may differentially influence recovery of rapid movements which benefit from the stretch-shortening cycle. Indeed, D'Amico and Gillis[19] speculated as much when they observed that FR had no influence on recovery of a squat jump, but enhanced recovery of agility performance. But in this view it becomes difficult to reconcile the lack of influence on agility finding observed herein with other studies that have found an attenuating effect of FR on agility decrements following EIMD.[19, 36] Notably, the subjects in each of the aforementioned studies were male, while the present investigation included both healthy male *and* female participants. It is possible that under the condition of the present experiment, females attained smaller agility recovery benefits from FR than their male counterparts. In support of this notion, Carlock et al.[37] reported that the gap between the squat and countermovement jump for males and females is 10% and 5%, respectively, suggesting that males rely on the stretch shortening cycle more than females in explosive tasks. In the present study the change from baseline area under the curve value (mean $\pm$ SD), representing the extent to which agility T-test time was impaired, was 2.9 $\pm$ 5.2. This can be contrasted with previous work, which observed a smaller value of 1.6 $\pm$ 2.8.[19] The larger variation observed in the present experiment may have prevented the observation of a significant difference between groups. Further, if FR indeed specifically influences tasks which utilize the stretch shortening cycle,[19] the inclusion of females may have diminished whatever difference is typically observed between FR and CON groups in all-male studies. At present, the majority of the existing evidence appears to support the use of FR for agility recovery in healthy males, though further investigation is needed.

In the present investigation, FR did not improve HRV or PWV, compared to CON. Lastova et al.[27] reported that FR improved HRV up to 30 minutes following treatment, and Okamoto et al.[26] reported that FR improved PWV up to 30 minutes following treatment. The present investigation assessed these indices of autonomic recovery 24 hours following each instance of FR, so as to minimize the influence of acute effects. Thus, it appears that the improvements in HRV and PWV induced by FR diminish sometime between 30 minutes and 24 hours post treatment. While short-lived improvements in autonomic variables could plausibly enhance recovery beyond the time frame when changes in those measures are apparent, that relationship was not evident within the confines of this investigation. The low reliability observed in the autonomic variables may have contributed to the null findings, as well. Reliability of HRV measures vary considerably throughout the literature,[38] potentially obscuring an autonomic influence of whichever independent variables are investigated. In any case, additional mechanisms beyond those previously discussed may have contributed to the observed reductions in muscle soreness, and may explain the accelerated recovery in performance measures observed in previous research. Improved blood flow has been observed with FR,[39] and this may indeed aid the recovery process following EIMD. Additionally, future researchers may consider examining the relationship between FR and inflammatory markers. McDonald et al.[8] speculated that reduced inflammation may play a role in the enhance recovery observed following FR, but this has not been directly explored. Investigations concerning the relationship between massage and inflammation have yielded conflicting results,[40,41] but examining the impact of FR on relevant markers following EIMD may provide new insights.

There were several important limitations to this study. First, the present findings may be unique to the particular FR protocol used in this investigation. At this time, no standard method, duration, or frequency of FR exists. Second, the findings of the present investigation are limited to recovery from EIMD following a repeated sprint protocol. Individuals experiencing EIMD brought on by other forms of exercise may respond to FR in a different manner. Third, the subjects who volunteered for the present study were healthy, college-aged individuals. Other, more specific populations who may or may not benefit from FR following EIMD cannot currently be determined. Fourth, the low reliability values of certain dependent variables i.e. agility, heart rate variability, pulse wave velocity, and gLMS may have contributed to the null findings. Reliability values were calculated using day two and three familiarization data from the baseline testing week, thus, a learning effect may have contributed to lower reliability as calculated in the agility T-Test. A learning effect would not likely contribute to lower HRV and PWV reliability values, so it is plausible that the particular autonomic assessments used in the present investigation have low reliability. Despite a significant difference observed in gLMS, the low observed reliability calls into question the reproducibility of this measure when an 18 inch step up is performed during its collection. Finally, neither subjects nor testers were blinded to the condition. The inability to blind those undergoing a FR treatment will likely remain an inherent limitation to research on the topic.

CONCLUSIONS

Data from the present investigation indicate that FR can reduce perceptions of muscle soreness compared to CON, following EIMD caused by sprinting. Conversely, the results indicate that foam rolling does not impact recovery of agility, enhance recovery of VJ, increase HRV, and decrease PWV compared to CON. Following EIMD, FR may be a beneficial tool for reducing perceptions of muscle soreness. The physiological mechanisms underlying these results remain unclear. Based on the present investigation, it cannot be concluded that the autonomic nervous system plays a role in the enhanced performance recovery associated with FR.

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